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Prediction of an Occupant's Motion During Rollover Crashes

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In order to understand an occupant's often violent and complicated motion during rollover accidents, the motion of an anthropomorphic dummy was predicted dynamically using the Articulated Total Body model, a human body gross motion simulation program. The accuracy of the predicted motion was established by its favorable comparison to that recorded on high speed film during a 60 mph crash in which the vehicle rolled over four times. This vehicle motion was then modified to six other rollover crash situations for computer simulation. Significant changes in the predicted occupant motion were readily observed. Differences were also observed in occupant accelerations and impact and belt forces. Keywo

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ABSTRACT

In order to understand an occupant's often violent and complicated motion during rollover accidents, the motion of an anthropomorphic dummy was predicted dynamically using a human body gross motion simulation program. The accuracy of the predicted motion was established by its favorable comparison to that recorded on high speed film during a 60 mph crash in which the vehicle rolled over four times. This vehicle motion was then modified to six other rollover crash situations for computer simulation. Significant changes in the predicted occupant motion were readily observed. Differences were also observed in occupant accelerations and impact and belt forces.

OCCUPANT MOTION during vehicle rollover accidents needs to be investigated because of the higher probability of suffering serious injury than in other crash modes. Based on the latest (1984) data from the National Accident Sampling System (NASS) (1)* there were 3,465,000 occupants in 1984 who were in towaway accidents i.e. accidents in which an incapacitating injury or fatality occurred or a vehicle required towing from the scene. Of these occupants, 287,000 were in vehicles which rolled over. The occupants in rollover crashes had a severe injury (AIS 3 or greater) rate of 5.4 percent, as opposed to only 2.1 percent for occupants of vehicles which did not roll over. Although only 8.3 percent of the NASS occupants were in rollover, this small percentage accounted for 18.8 percent of the severe injuries.

A motor vehicle often undergoes violent and complicated motion during an accident in which rollover occurs. The motion of the vehicle's occupants will also be violent and complicated, and may include total or partial ejection. Full-scale motor vehicle rollover crash tests are expensive and it is possible to effectively control only the initial motion of the vehicle prior to its rolling over. The features of the rollover event, such as the number of rolls and the distance of travel after the initiation of rollover cannot be accurately predicted or controlled. In order to understand the potential for injury during rollover, the effects on the occupant's motion need to be studied for a variety of crash situations for which rollover occurs. Such a complex and detailed study can only be accomplished by a computer program. Computer simulations of occupant motion during rollover have been previously done only in 2-dimensions (2). For complete simulation of the six degree-of-freedom vehicle motion that usually occurs in rollovers a 3-dimensional model is needed.

The Armstrong Aerospace Medical Research Laboratory (AAMRL) has for a number of years been performing predictive simulations of human body dynamics using the gross motion computer-based Articulated Total Body (ATB) model. This model, which is an enhanced version of the Crash Victim Simulator (CVS) developed for the National Highway Traffic Safety Administration (NHTSA), has been used by the Air Force to investigate human response to dynamic environments such as horizontal impacts, aircraft ejections and sustained accelerations.

Because of the ATB model capabilities it was used to simulate the motion of a belt restrained Part 572 dummy occupant during a staged 60 mph rollover crash in which the vehicle made four complete rolls in 4.5 seconds (3). This simulation was used to

*Numbers in parentheses designate references at end of paper.

develop the methods for using the ATB model to predict occupant dynamics during rollover. The actual test results for the rollover event compared favorably with the simulation results. This meant that the forces acting on the occupant, such as belt and seat forces had been modeled adequately.

It was then assumed that the modeling of these forces would remain valid in other rollover crash situations. Using this assumption, six additional ATB simulations have been made in which the motion of the vehicle was changed from that observed during the staged crash in order to study the corresponding changes to the occupant's motion. The changes to the vehicle motion consisted of added impacts to the initial vehicle motion and of applied vehicle deceleration at various points during the roll.

MODEL DESCRIPTION

The ATB model is an enhanced version of the Crash Victim Simulator (CVS) model developed by Calspan for the NHTSA (4). The enhancements and modifications have been made to improve the model's capabilities and application to Air Force requirements (5, 6). AAMRL has used the ATB model extensively to study human body dynamics in aircraft ejections, sustained accelerations, and automobile panic braking (7, 8). The ATB model and its associated three-dimensional body graphics display program, VIEW (9), are run on AAMRL's Perkin-Elmer 3200 series computers.

The model is based on rigid body dynamics, which allows the body to be described as a set of body segments, coupled at joints which allow the application of torques as functions of joint orientations and rate of change of orientations. External forces are applied to the segments through interaction with other segments, planes used to describe the environment, belt restraint systems, outside pressure such as wind forces, and gravity. Each segment has a surface approximated by an ellipsoid which is used to determine amount of contact, surface area, or application point for these forces. Motion constraints can also be placed on or between segments.

Many highly complex dynamic systems that can be described in terms of multiple rigid bodies can be solved with the ATB model because of its generality and flexibility. Specific applications of the model are defined by an input data set consisting of the geometrical, inertial and material properties of the segments; the joint characteristics; definition of the environment such as contact planes; belts; wind forces; and time histories of known motions. For this application, fifteen segments coupled by fourteen joints are used to describe the body.

Time history data for the motion of all segments, joint orientations and torques, and internal and external forces are available from the model. Body position graphical plots are obtained using the VIEW graphic display program which depicts each body segment as a three-dimensional ellipsoid and also shows the vehicle surfaces.

VALIDATION SIMULATION

A particularly violent and complex vehicle rollover crash test was chosen to be simulated with the purpose of developing procedures for rollover modeling. The specific crash test was a partially controlled test in which a 4-door Dodge Aries, with a belt restrained Part 572 dummy in the front passenger seat, traveling at 60 mph was released to travel up a ramp created by burying the turned down end of a guardrail. The resulting motion consisted of four full rotations in 4.5 seconds with the vehicle coming to rest about 200 ft from the first guardrail contact (Fig 1).

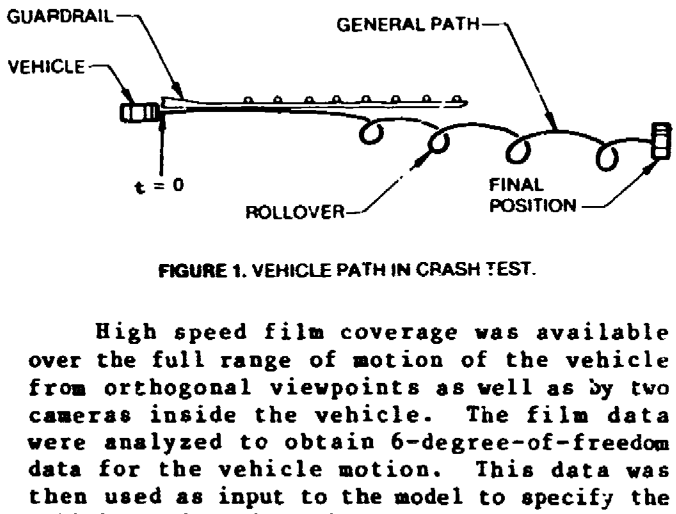


FIGURE 1. VEHICLE PATH IN CRASH TEST.

High speed film coverage was available over the full range of motion of the vehicle from orthogonal viewpoints as well as by two cameras inside the vehicle. The film data were analyzed to obtain 6-degree-of-freedom data for the vehicle motion. This data was then used as input to the model to specify the vehicle motion time history. Also available from the test were accelerometer data and roll rate gyro data of the vehicle and the manikin head and chest.

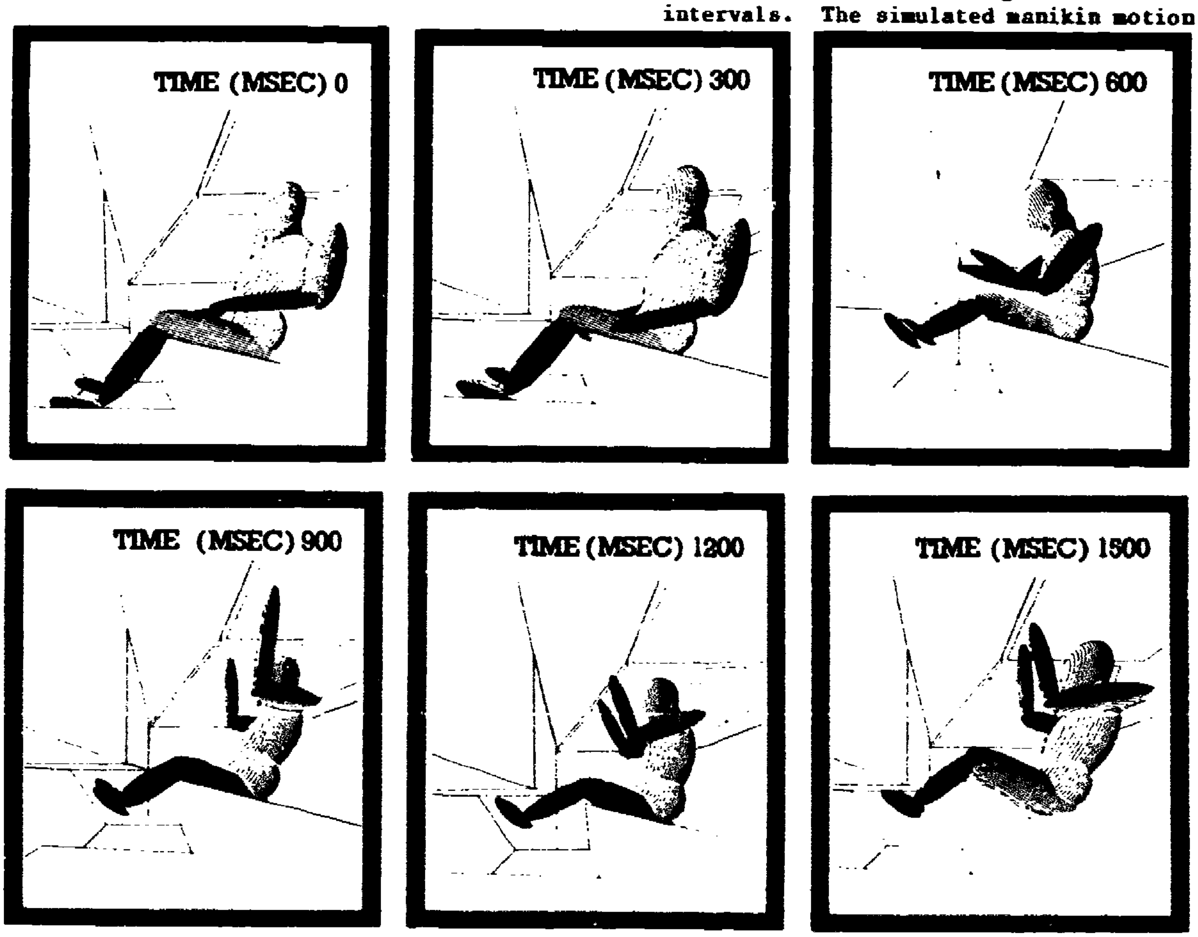
SIMULATION DESCRIPTION - Considerable information is required for the simulation of a crash test, including the segment and joint characteristics of the manikin, the geometry of the vehicle interior along with force deflection characteristics for each possible impact within the vehicle, and the seat belt configuration. The manikin used in the crash test was the Alderson Part 572 dummy. The model description used in prescribing segment inertial and geometric properties and joint locations and resistive characteristics of the manikin was obtained from the Validation of the Crash Victim Simulator Report, Volume 2 (4). This model is composed of 15 ellipsoidal

contact segments, each having the inertial and surface material properties taken from a Part 572 manikin. These segments are overlapped and attached to each other at fixed points representing an actual joint location or pivot point which best approximates the manikin's complex articulation. The joint's pivot points remain fixed relative to their associated segments and have ranges of motion and resistive properties appropriate for the articulations which they represent. For example, the manikin knees pivot around a straight shaft. Therefore a pin joint is used to model the knee. The torso and neck articulate by means of rubber cylinders able to bend in any direction. Consequently those joints are mathematically modeled as universal joints. The hip, shoulder, elbow and ankle joints were constructed with more complex articulations. Euler type rotations are used to model these joints.

A 1982 Dodge Aries with a bench seat was used in this test. Measurements of the car interior were used to define contact planes representing each potential interacting surface in the vehicle. Potential contacts between a body segment and a vehicle surface were identified and a force deflection function defined for each. The force deflection functions used were those used with good results in the 1980 Child Impact Study (8).

The manikin is held in the passenger seat by a harness consisting of a standard automotive lap and shoulder belt. The two belts are anchored to the car and have a number of attachment points that are allowed to slide on the contact ellipsoid surface of the body segments. The lap belt lies across the lower torso and the shoulder belt lies across the lower, middle, and upper torso segments. Two additional contact ellipsoids are used to provide a better surface contour for the belts to slide on. For example, an ellipsoid is attached to the upper torso in order to form an appropriate shoulder geometry that the ellipsoidal shape of the upper torso segment lacks.

SIMULATION RESULTS - In the test, the manikin motion was filmed by two cameras mounted within the car. The rear camera, in the back seat faced forward and viewed mostly the head and arm motion. The front seat camera was mounted underneath the steering wheel and pointed slightly upwards to view the entire manikin. These camera locations were used as viewpoints in the VIEW program in order to compare the manikin motion in the test event with the simulation. The resulting VIEW graphics from the simulation corresponding to the view from the front camera are shown in Figure 2 at 300 msec intervals. The simulated manikin motion is



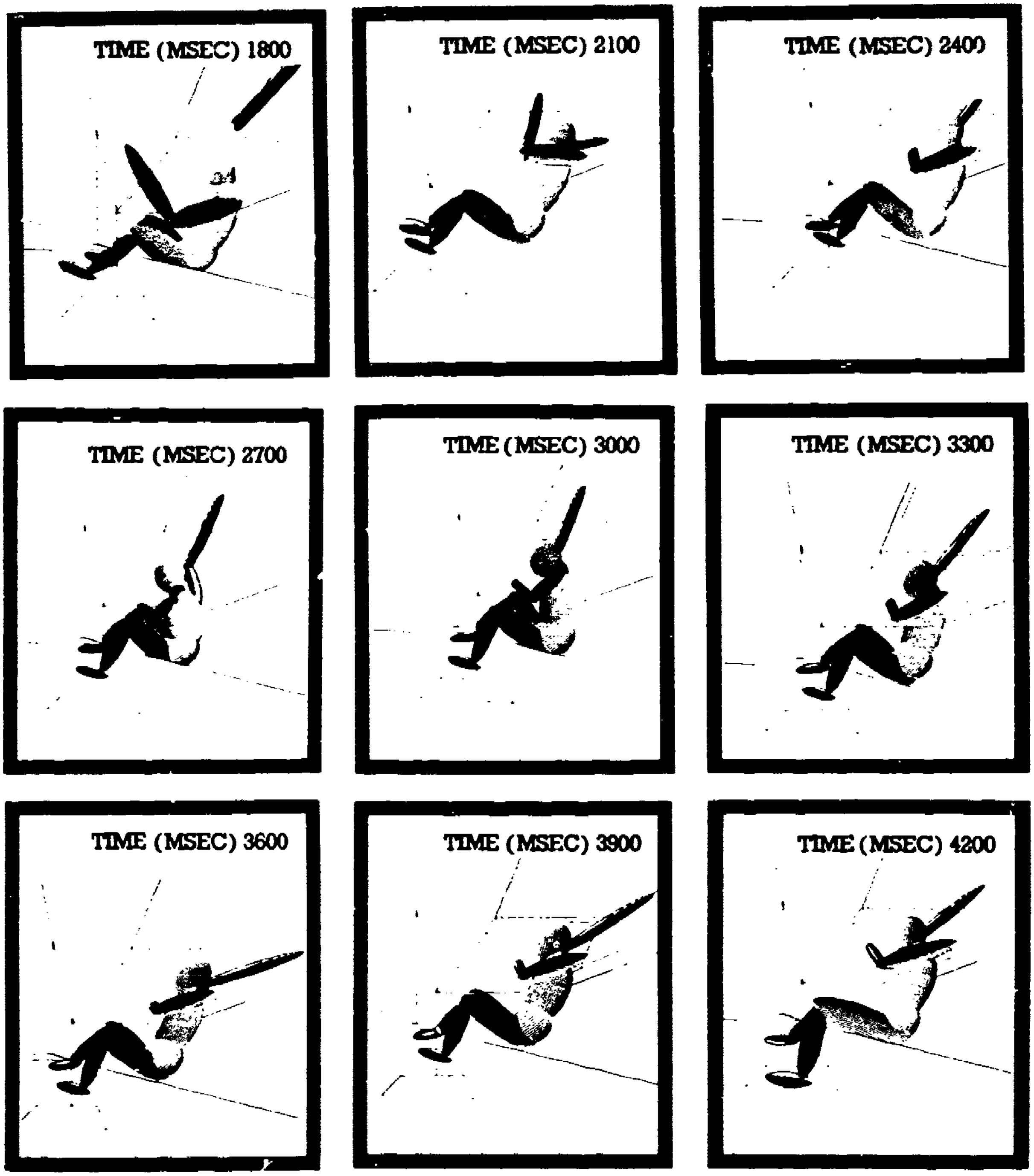


FIGURE 2. VIEW GRAPHICS OF THE ORIGINAL CRASH TEST SIMULATION FROM THE FRONT CAMERA LOCATION AT 300 MSEC INTERVALS.

seen to be minimal during the first second, with the body leaning forward against the door. The most violent motion occurs between one and two seconds when the vehicle is completely upside down for the first time. The manikin hangs from the lap belt and is thrown towards the driver's seat as the car rights itself. After this the harness belt and the centrifugal force pull the body back towards the passenger side. Thereafter, the vehicle's rotation keeps the manikin high in the seat and against the side door until almost four seconds have elapsed when the vehicle motion slows and the body settles back into the seat.

As described in Ref. (3), this simulated motion compares favorably to the manikin motion filmed during the test. The limbs in the simulation are generally stiffer than in the actual event, but the torso motion is especially good with only minor phase shifts between the simulated and actual motion. The main factors contributing to the phase differences appeared to be imprecise vehicle motion prescription. Also the assumed harness belt stiffness and the damping associated with body and vehicle contacts may have contributed. The reconstruction of the vehicle motion from high speed film data was in general successful. However, this process of reconstruction tended to filter out the abrupt acceleration of the vehicle during rail and ground impacts. While the motion of the occupant is mainly dictated by the gross motion of the vehicle, the small and abrupt accelerations can be expected to produce phase shifts.

MODIFIED SIMULATIONS

With the technique developed and validated for using the ATB model to simulate the manikin motion during a complex rollover event, different vehicle motions can be investigated. The vehicle motion input for the test simulation data consisted of X, Y and Z linear displacements and yaw, pitch and roll angular displacements at 50 msec time steps. In order to study controlled differences in vehicle motion, the vehicle motion data collected from the test were modified. Six simulations were made with modified vehicle motions while all other input parameters such as the manikin description, vehicle geometry, and seat belt configuration were unchanged from the test simulation.

VEHICLE MOTION CHANGES - Many rollovers are preceded by an initial vehicle impact. To investigate the effects of a large impact prior to the initiation of rollover, a 5 to 10G frontal deceleration was imposed at the beginning of the vehicle motion from the crash test. The first simulation had an impact, which decreased the vehicle velocity from 60 to 50 mph before any rolling began. The second simulation had a stronger impact, which decreased the vehicle velocity from 60 to 30 mph before any rolling began.

In the crash test simulation the vehicle's velocity dropped from 60 mph to 50 mph in the first 400 msec and the vehicle experienced a peak deceleration of 2 G's (Fig 3). In the first modified simulation the same velocity drop occurred in 150 msec resulting in a peak deceleration of 6.2 G's. The x-axis (along the guardrail) linear displacement data were adjusted to incorporate this change while keeping the velocity curve smooth. The other linear and angular displacement data sets were left unchanged except to start at 150 msec when the x-axis velocity had dropped to 50 mph. A similar modification was made for the second modified simulation in which the initial impact decreased the velocity from 60 mph to 30 mph. This 30 mph velocity drop was forced to occur in 300 msec rather than the 1800 msec it took in the crash test. This required a peak deceleration of 8.5 G's.

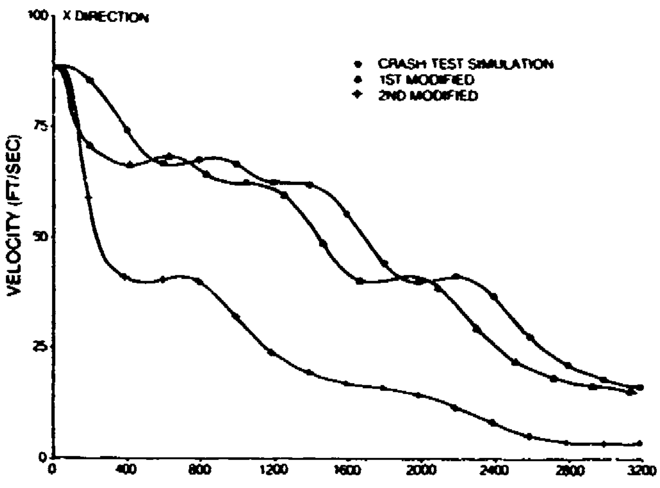


FIGURE 3. VEHICLE FORWARD VELOCITY IN THE ORIGINAL VALIDATION SIMULATION AND THE TWO INITIAL IMPACT SIMULATIONS

Also of interest is how protected is an occupant during the rollover. Seat belts and automobile interiors are primarily designed for protection during impacts with the vehicle and occupant upright. Their role in protecting the occupant from an impact when the automobile and/or the occupant is out of position, such as during a rollover requires further study. In the original vehicle motion, there is a time period between 2000 and 3500 msec when the rolling motion of the car is dominant. By adding an impact during this motion, the effects of the impact on the manikin, while the car and manikin are out of position, can be investigated. Four different simulations were set up to study this type of impact. The impacts were chosen to bring the

vehicle to a complete stop as if the vehicle had rolled into a tree or embankment. The four cases were defined by the vehicle's ending position: A) upright; B) on the passenger's side; C) upside down; and D) on the driver's side (Fig 4).

FIGURE 4. FINAL VEHICLE POSITIONS

For each of these cases both the linear and angular displacement data sets were modified. In order to bring the vehicle to a complete stop in the upright position, for case A, the original vehicle velocities were modified from a time point during the rolling phase slightly before the vehicle reached the upright position. The decelerations levels were kept below 10G's by controlling the time interval in which the vehicle was stopped. The angular motion was adjusted in the same manner, using a scaling factor to stop the motion in the same time interval. Similar modifications were made for the other three cases, forcing the vehicle to stop in the correct position. The resulting x-axis linear velocities are shown in Figure 5. The deceleration maximum and the impact initiation time for each case is A) 7.7 G's, 2500 msec; B) 3.8 G's, 2650 msec; C) 7.3 G's, 2900 msec;

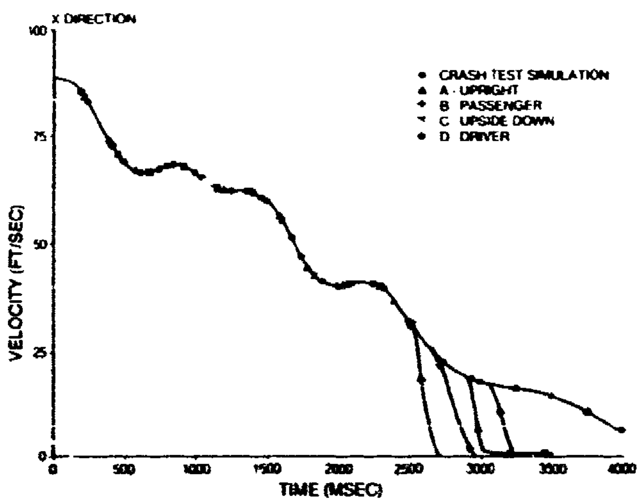


FIGURE 5. VEHICLE FORWARD VELOCITY IN THE ORIGINAL VALIDATION SIMULATION AND THE FOUR ROLLING IMPACT SIMULATIONS

and D) 4.6 G's, 3050 msec. Smaller decelerations were used for case B and D, because the roof and suspension would provide more vehicle deformation in these cases. The resulting peak angular decelerations are for simulation A, 3930 deg/sec^2; B, 2420 deg/sec^2; C, 5032 deg/sec^2; and D, 3775 deg/sec^2.

RESULTS

The VIEW plots of the manikin motion from the two initial impact simulations show a pronounced forward motion during the added impacts (Fig 6 & 7). The head actually impacts the dash in both simulations. Comparing the subsequent motion with the original simulation, the initial impact simulations react more violently to the rollover event. This is probably due to the manikin and belt being out of position when the rolling motion begins.

Figures 8, 9 and 10 contain the VIEW plots of the last time frames of simulations B, C and D respectively. The beginning motion of these simulations is the same as the original simulation as shown in Figure 2. In simulation B the vehicle comes to rest on the passenger side. The manikin is thrown to the passenger door at 2700 msec, and as the vehicle motion dies out the manikin settles against the door and seat.

The vehicle in simulation C comes to a rest on its roof, causing a large lateral deceleration. This deceleration throws the manikin towards the driver's seat beginning at 3000 msec. At the end of the simulation the manikin hangs from the lap belt with its feet trapped by the dash.

The deceleration caused by stopping the vehicle on the driver's side in simulation D pushes the manikin into the seat at 3300 msec. With the vehicle at rest the manikin then falls towards the driver's seat while being held by the lap belt.

For simulation A where the vehicle comes to a rest upright, the manikin was placed in the driver's seat, because the impact on the passenger side of the car needed to stop the vehicle in this position would cause deformation of the passenger side. The resulting manikin motion is considerably different from the other simulations (Fig 11). As the vehicle first rolls to its side at 1200 msec the manikin falls towards the passenger side which is on the ground. The harness belt and centrifugal force then pull the manikin back and keep it against the door until the stopping impact throws the manikin to the passenger seat at 2700 msec. The belt pulls the manikin back as the vehicle is stopped.

Besides the kinematic data shown in the VIEW graphics of each simulation, the ATB model provides time histories of dynamics data such as body segment accelerations and belt and contact forces. The belt forces are

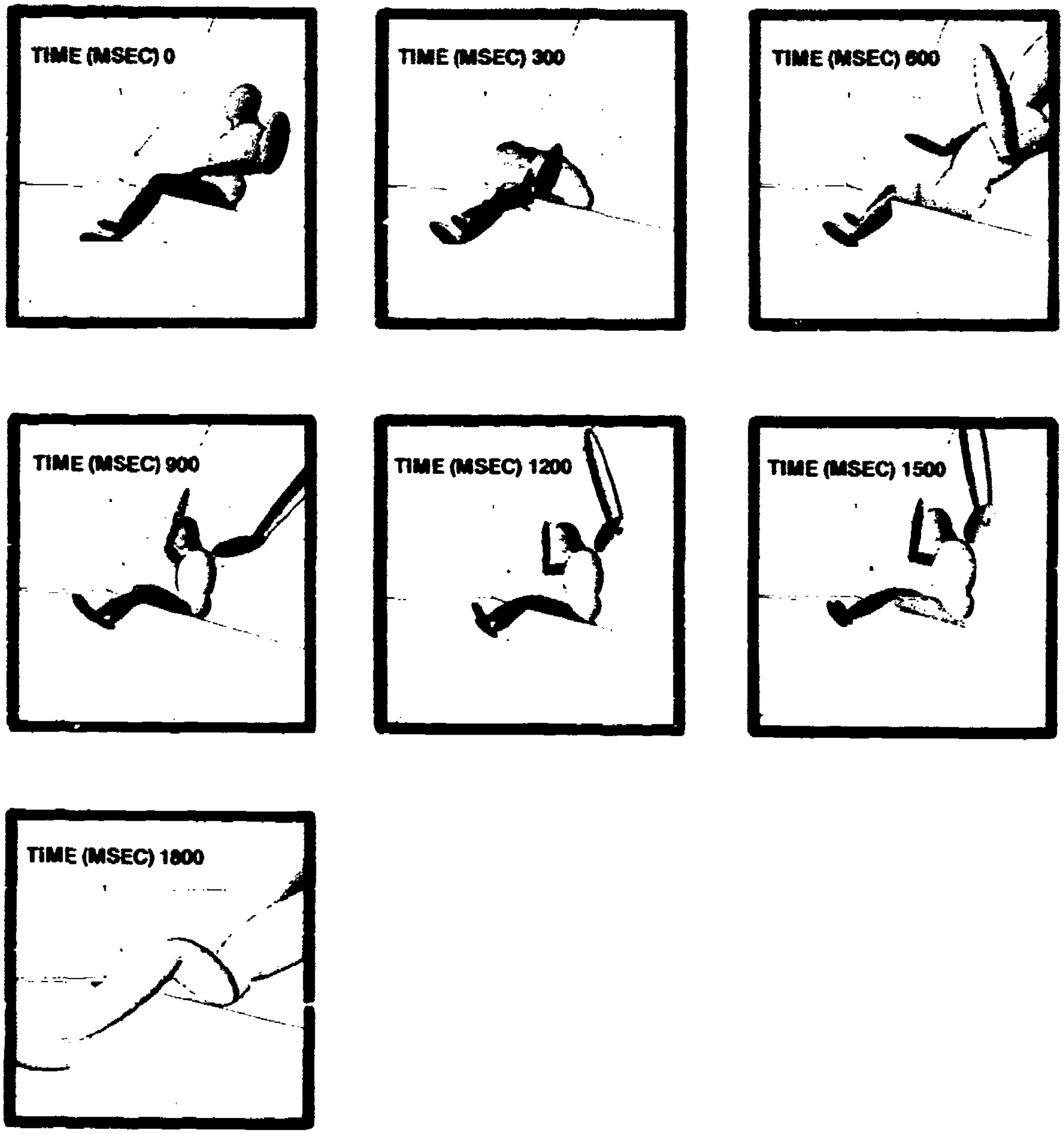


FIGURE 6. VIEW GRAPHICS FROM THE FIRST MODIFIED SIMULATION WITH THE 10 MPH INITIAL DROP IN VELOCITY.

provided at the vehicle anchor points. For these simulations the belt time histories have peaks usually ranging between 250 and 600 lbs. For example, the lap belt door anchor point forces during simulation C (Fig 12) average 250 lbs for most of the simulation. Soon after 3000 msec, when the impact takes place, a peak of 545 lbs occurs. The peaks are rarely larger than 600 lbs in any of the simulations except during the largest impacts, when a few peaks are almost 2000 lbs.

The impact forces between body segments and the vehicle are generally mild. Only the two initial impact simulations have an impact between the head and dash (Fig 13 & 14). The 6.2 G initial deceleration in the first modified simulation caused a 270 lb impact of the head with the dash while the 8.5 G deceleration in the second simulation caused a 320 lb impact of longer duration. The

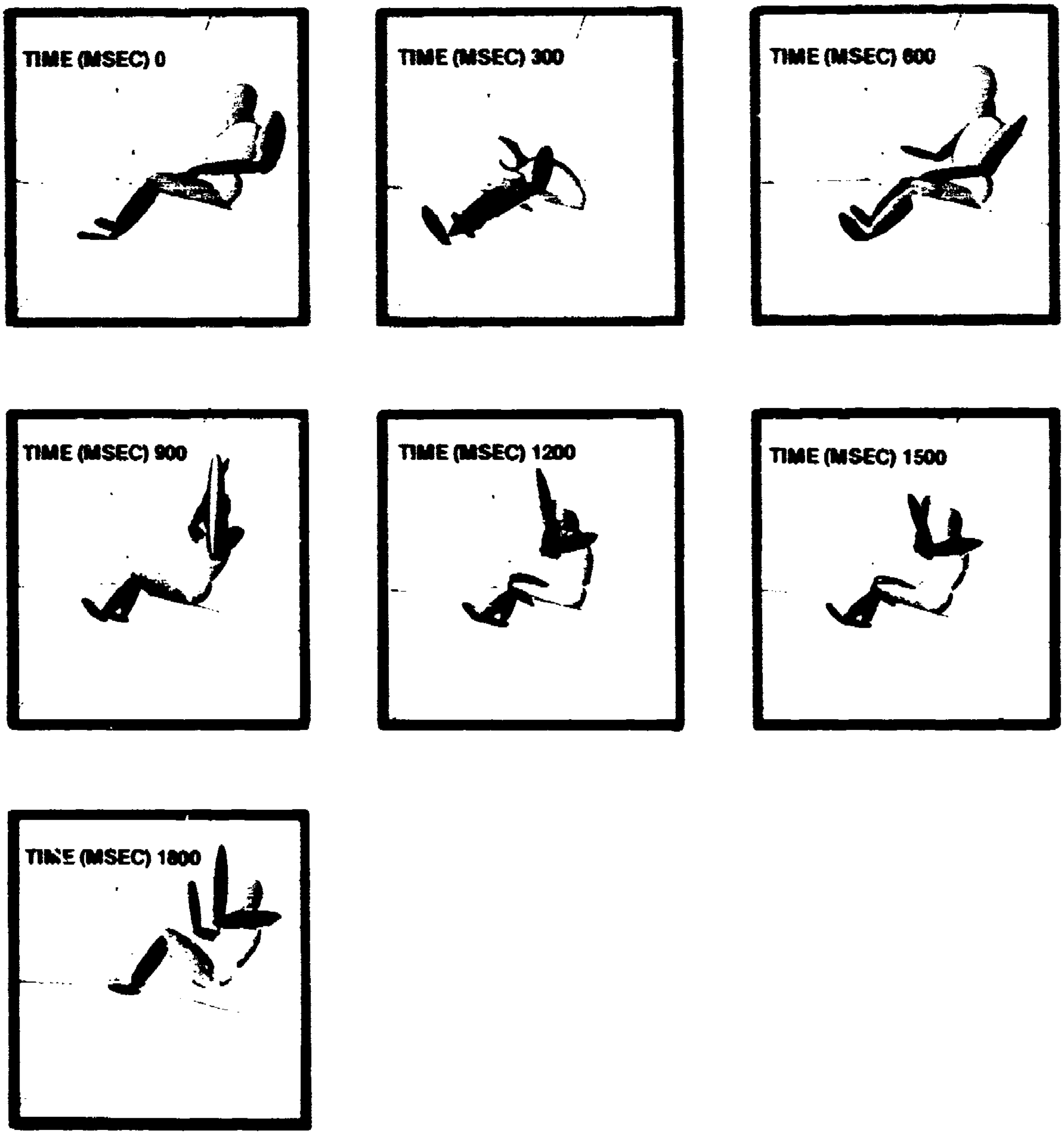


FIGURE 7. VIEW GRAPHICS FROM THE SECOND MODIFIED SIMULATION WITH THE 30 MPH INITIAL DROP IN VELOCITY.

knee/dash impacts for these two simulations are similar in magnitude and duration to the head/dash impacts.

The other significant impacts that occurred were with the side windows and doors during the vehicle's rolling motion. The window impacts often produced large instantaneous forces as seen in Figure 15 where the force between the right upper arm and the side window reaches 800 lbs. The door impacts have lower magnitudes but are more sustained (Fig 16). These impact forces are the same for the crash test simulation and simulations B, C, and D until 2500 msec, when the added decelerations start taking place. The added decelerations in simulations A through D do result in some additional side impacts, but the forces from these additional impacts were all small in magnitude. For example in Figure 17, the right upper arm

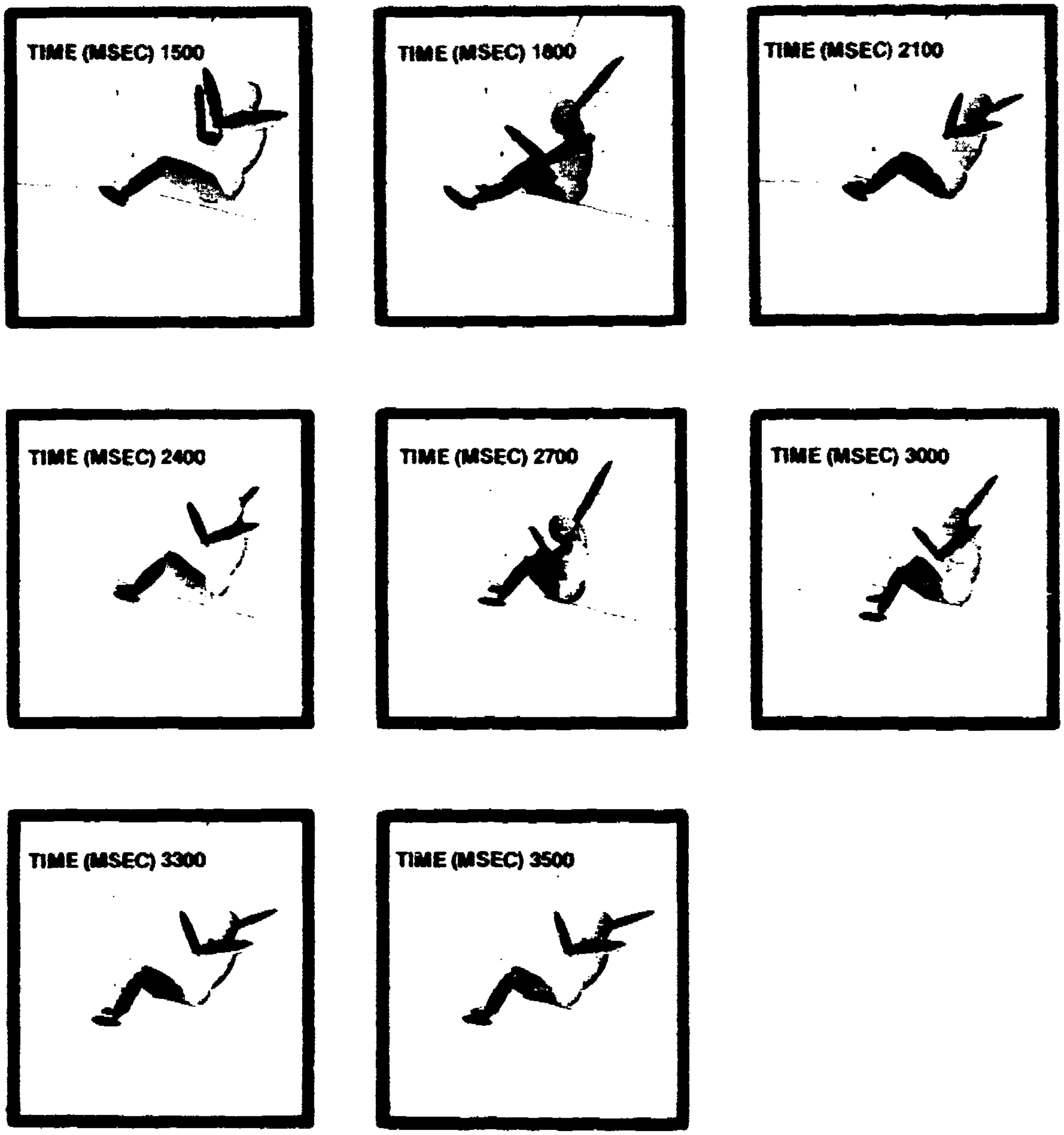


FIGURE 8. VIEW GRAPHICS AFTER 1500 MSEC FROM SIMULATION B IN WHICH THE VEHICLE COMES TO A REST ON THE PASSENGER'S SIDE.

impacts the side door due to the added deceleration in simulation B, but the resulting force is only 45 lbs. Some head/roof contact was expected in these simulations, because the vehicle is often completely upside down. The belts apparently held the manikin sufficiently close to the seat because none of the seven simulations had head/roof contact. The only head/roof contact in the actual crash test occurred near the side doors.

The two initial impact simulations have head accelerations as high as 30 G's from the head/dash impact. After this impact the head accelerations rarely get as large as 8 G's, even during times of violent motion. The head accelerations in the other simulations are never more than 12 G's. The head accelerations due to the added vehicle accelerations are between 10 and 12 G's for simulations A, B, C and D.

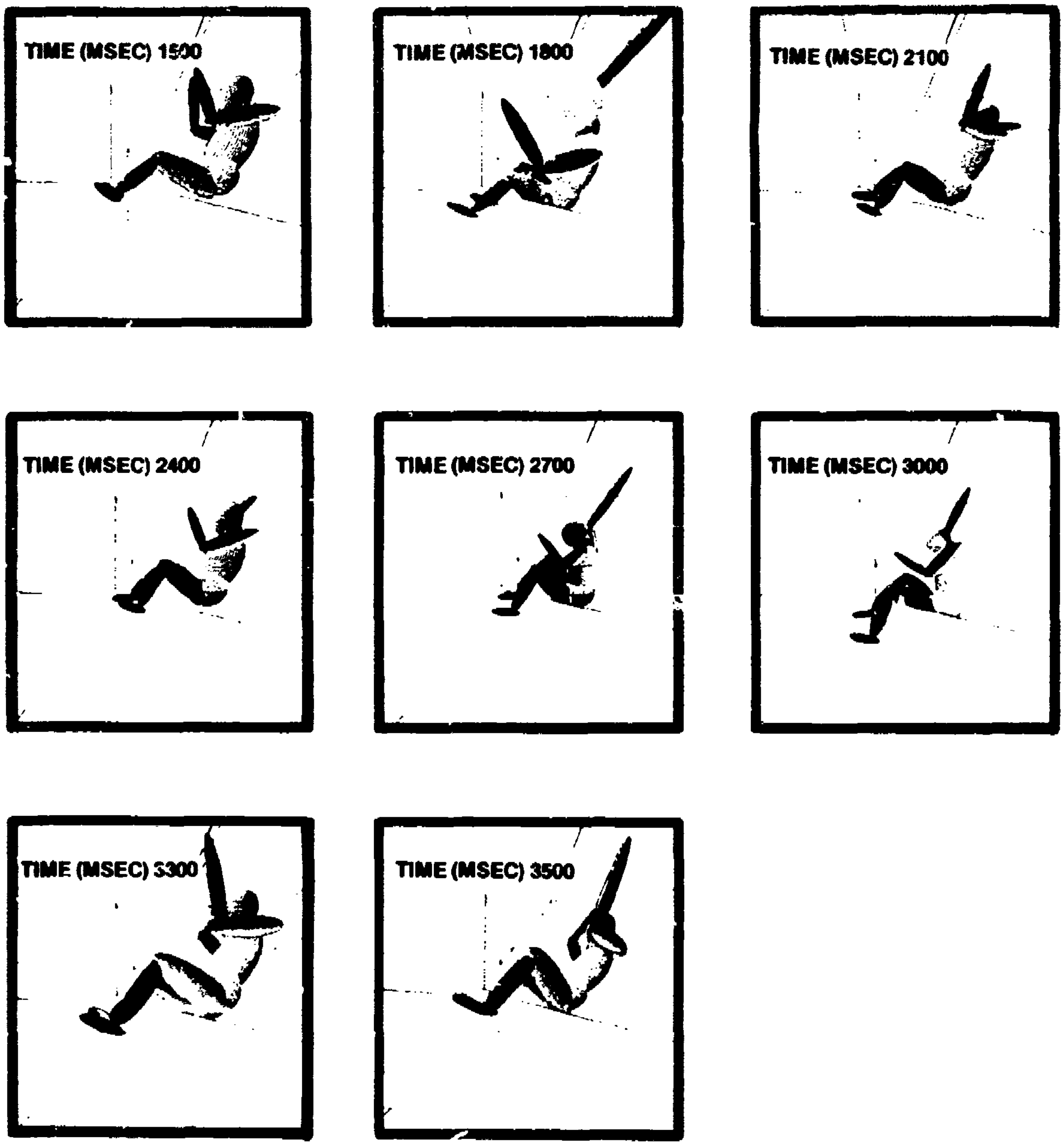


FIGURE 9. VIEW GRAPHICS AFTER 1500 MSEC FROM SIMULATION C IN WHICH THE VEHICLE COMES TO A REST ON ITS ROOF.

CONCLUSIONS

It is apparent that the mechanisms of injury during rollover vary from those in frontal impact accidents. The head accelerations during the rollover simulations without the added frontal impacts are milder than those with frontal impacts. The large head, knee, and chest impacts, usual causes of injury in frontal impact accidents are not always present during rollover with a belted occupant. The simulations show that limb flailing and lateral head impacts are more likely sources of injury during rollover. In spite of the belt restraints the occupant in these simulations went through a lot of motion. From this it can be expected that the motion of an unrestrained occupant would be more violent and in all likelihood result in multiple impacts within the vehicle.

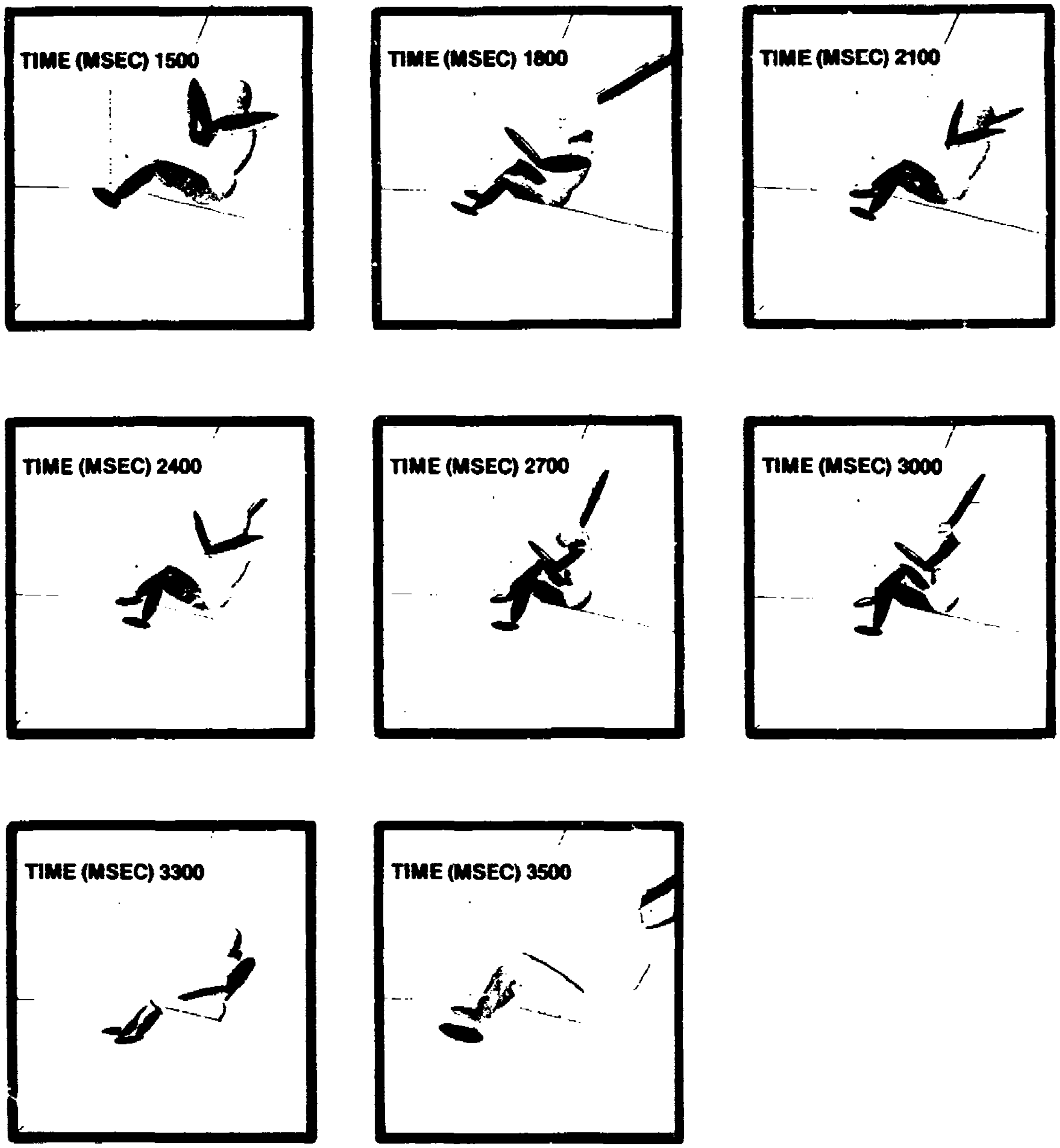


FIGURE 10. VIEW GRAPHICS AFTER 1500 MSEC FROM SIMULATION D IN WHICH THE VEHICLE COMES TO A REST ON THE DRIVER'S SIDE.

The shoulder belt is valuable in restraining the occupant in an initial frontal impact, but early in all seven simulations the occupant fell to the side, sliding out of the shoulder belt. With the occupant out of the shoulder belt, the upper body was free to move around, but the occupant was still well restrained by the lap belt.

This study also demonstrated that the ATB model is a valuable tool in the investigation of an occupant's motion during a crash in which rollover occurs. The model is capable of simulating violent and complicated occupant motion for crash events lasting well over 3 seconds. NHTSA and AAMRL are currently simulating more staged rollovers with both restrained and unrestrained occupants in order to provide a more complete validation of the ATB predictive simulation techniques. With the model completely validated its

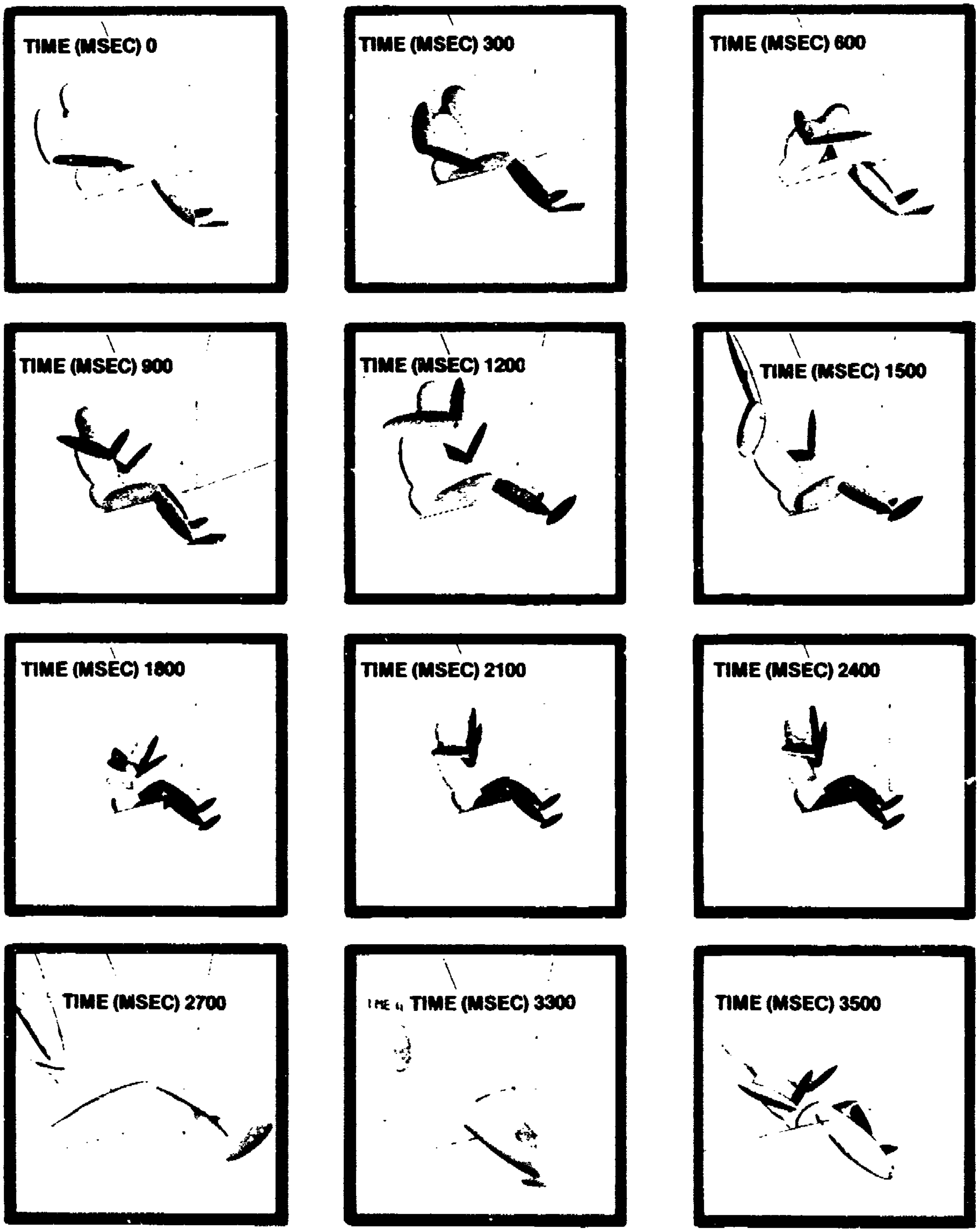


FIGURE 11. VIEW GRAPHICS FROM SIMULATION A IN WHICH THE VEHICLE COMES TO A REST UPRIGHT.

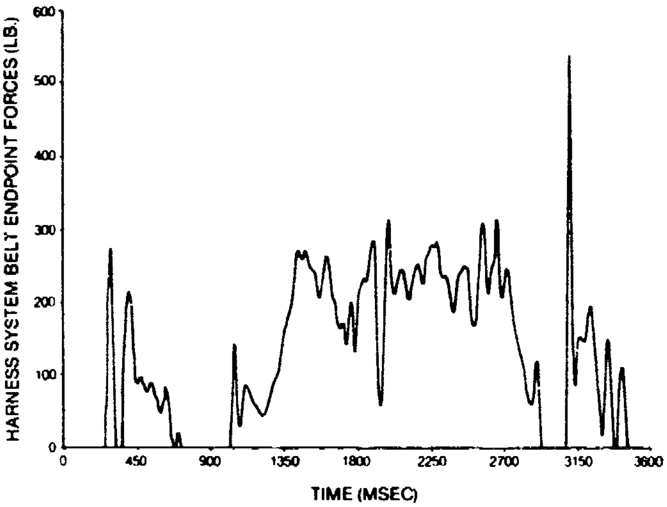


FIGURE 12. LAP BELT DOOR ANCHOR POINT FORCES IN SIMULATION C

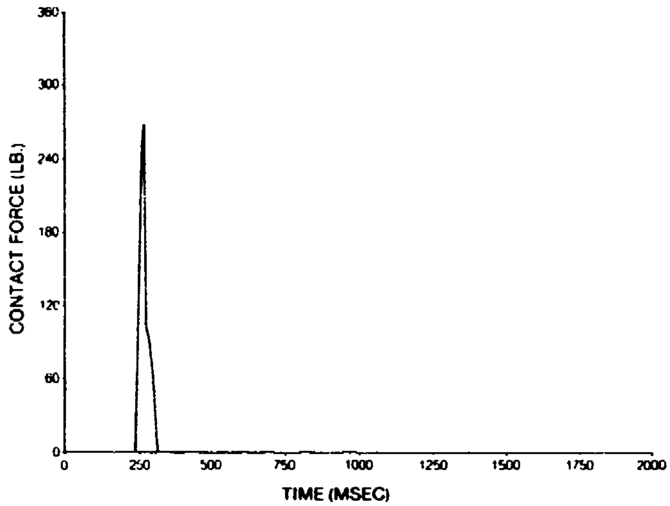


FIGURE 13. HEAD IMPACT FORCES WITH THE DASH DURING THE MODIFIED SIMULATION WITH THE 10 MPH INITIAL DROP IN VELOCITY

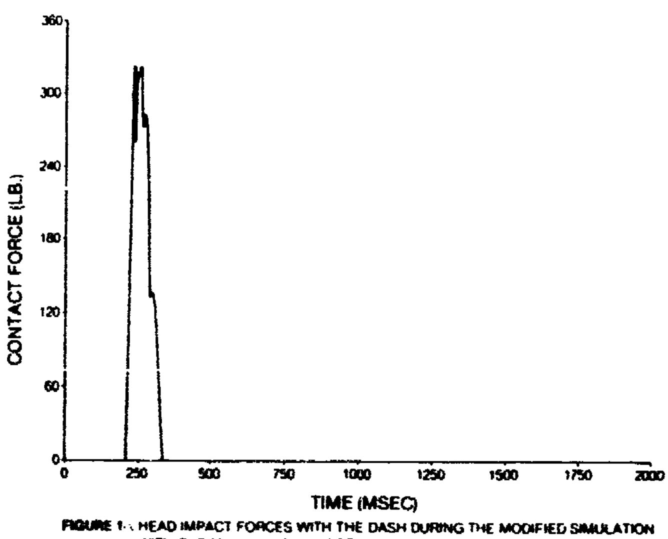


FIGURE 14. HEAD IMPACT FORCES WITH THE DASH DURING THE MODIFIED SIMULATION WITH THE 30 MPG INITIAL DROP IN VELOCITY

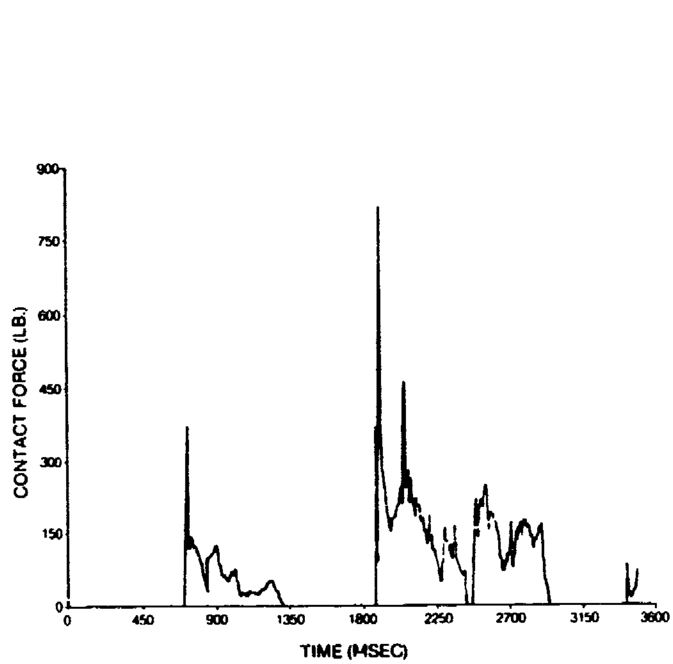


FIGURE 15. RIGHT UPPER ARM IMPACT FORCES WITH THE SIDE WINDOW DURING SIMULATION C

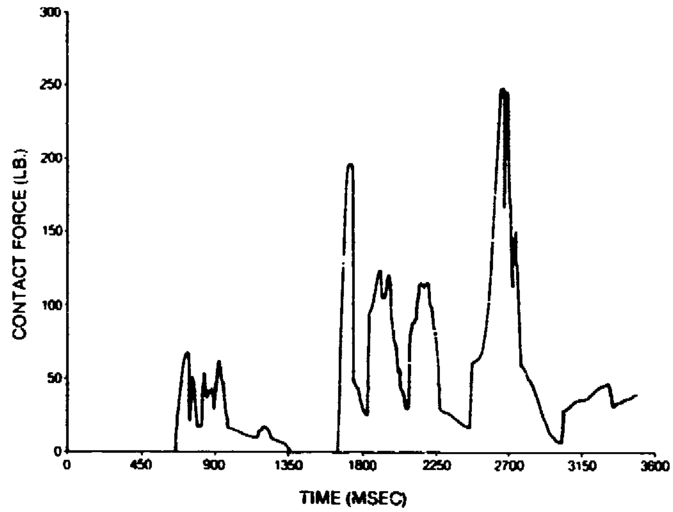


FIGURE 16. RIGHT UPPER LEG IMPACT FORCES WITH THE SIDE DOOR DURING SIMULATION B

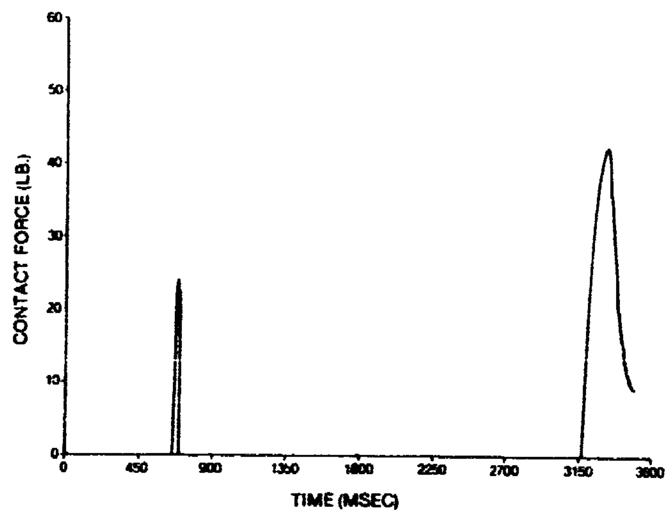


FIGURE 17. RIGHT UPPER ARM IMPACT FORCES WITH THE SIDE DOOR DURING SIMULATION B

effectiveness in predicting occupant motion during rollover can reduce the need for expensive full scale vehicle rollover crash tests. The ATB model also makes parametric studies possible, because of its capability to provide repeatable rollover crashes while varying specific parameters such as vehicle geometry, force deflection characteristics, occupant size, belt stiffness, and restrained or unrestrained occupant.

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